MASTER OF SCIENCE
IN
AERONAUTICAL ENGINEERING

VULNERABILITY REDUCTION OF MODERN TACTICAL AIRCRAFT
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Survivability engineers and Program Managers (PMS) must ensure that modern combat aircraft will be both mission effective and affordable by "designing in" survivability. Survivability means avoiding hits and when hit, withstanding the hits. Vulnerability has been defined as the inability of an aircraft to withstand the damage caused by a hostile environment. Most current tactical aircraft incorporate many vulnerability reduction features to reduce the likelihood of an aircraft kill given a hit (Pk/h), thereby increasing the aircraft's survivability. The goal of vulnerability reduction is to prevent critical damage "hit" caused failures, to mitigate cascading threat effects, and to allow for graceful degradation of an aircraft. The next-generation tactical aircraft under development is the Joint Strike Fighter (JSF). The JSF must be designed not only to avoid being hit, but also to survive when hit. This thesis presents the latest vulnerability reduction designs, features, and guidelines that can be used to reduce the vulnerability of the JSF.

INCORPORATION OF A DIFFERENTIAL GLOBAL POSITIONING SYSTEM (DGPS) IN THE CONTROL OF AN UNMANNED AERIAL VEHICLE (UAV) FOR PRECISE NAVIGATION IN THE LOCAL TANGENT PLANE (LTP)
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The purpose of this thesis is to incorporate the Global Positioning System (GPS) and Inertial Navigation System (INS), for the guidance of an unmanned aerial vehicle (UAV) seeking precise navigation in a Local Tangent Plane (LTP). By applying the Differential Positioning technique, GPS position data becomes more accurate. This position can then be referenced to a known location on the ground in order to give the aircraft's position in the Local Tangent Plane.

The FOG-R UAV at the Naval Postgraduate School will be used for autonomous flight testing using a Texas Instruments TM5320C30 Digital Signal Processor (DSP). This DSP is hosted on an IBM compatible PC, and is controlled via Integrated System's ACl00 control system design and implementation software package.

The GPS receiver used throughout this thesis is a Motorola PVT-6 OEM. Another identical GPS receiver is used as a reference station, thus providing the Differential capability. The objectives of this thesis are to: ensure the system is able to accept current location from the GPS and convert it to LTP, display the LTP coordinates (numerically and graphically), and be able to easily change the origin coordinates. Finally, the achieved accuracy of the differential setup is examined.

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

A STUDY OF THE EFFECTS OF ON-BOARD ELECTRONIC COUNTERMEASURES (ECM) ON THE COMBAT SURVIVABILITY OF AIRCRAFT (U)

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On-board electronic countermeasures increase aircraft survivability by reducing the likelihood that the aircraft will be hit by a radar guided missile. The cost of developing and maintaining ECM equipment must be justified by the increase in survivability since these actions require money and incur aircraft design penalties, such as increased weight. By examining ECM's effect on missile miss distance using statistical parameters, a quantifiable increase in miss distance due to ECM may be determined. Consequently, this thesis gathers and examines available data (from computer simulations, hardware-in-the-loop tests, and open-air tests) on the effects of ECM on missile miss distance. When combined with the missile warhead's lethality in an endgame study, an overall value for the increase in survivability may be determined.

DETERMINATION OF HUB FORCES AND MOMENTS OF THE RAH-46 COMANCHE HELICOPTER

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Efforts to establish a better understanding of the performance of the RAH-66 *Comanche* helicopter were performed as part of an engineering internship with the Sikorsky Aircraft Comanche Dynamics group in Trumbull (Stratford), Connecticut. Test data from whirl stand testing and the *Comanche* Propulsion System Testbed (the ground test vehicle replacement) was evaluated. Fixed and rotating frame measurements were used to determine hub moments and forces generated by cyclic inputs. Flapping response phase to control input was also determined. Other mast loads were examined to determine the cause for greater than anticipated hub forces. Edgewise bending of the rotor blades was found to be a significant contributor to hub forces.

A STUDY OF THE EFFECTS OF COUNTERMEASURE DISPENSER LOCATION ON INFRARED DECOY EFFECTIVENESS (U)

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The latest generation of infrared guided missiles employs a wide variety of techniques designed to discriminate between the target aircraft and flares. As a result, every aspect of a flare design and employment has become increasingly important. In response to the threat, countermeasure designers are having to rethink countermeasure design and employment.

This study focuses on one aspect of the problem facing countermeasures designers, that of dispenser location. To that end the effectiveness of the current SH-60B Seahawk dispenser locations will be compared to those of the planned SH-60R. Each configuration will employ pyrotechnic and pyrophoric flares against a counter-countermeasures capable threat in hovering, non-maneuvering and maneuvering scenarios.

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

EDUCATIONAL MATERIALS FOR THE IMPLEMENTATION OF SURVIVABILITY IN COMBAT AIRCRAFT DESIGN

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This thesis presents the educational objectives, and the means to achieve the objectives, essential for the implementation of aircraft combat survivability in design. Achieving the educational objectives forms the basis of a student's knowledge and proficiency within the aircraft survivability discipline. To realize the goal of this thesis, the specific educational objectives for aircraft survivability had to be reviewed, refined, and further developed. The educational objectives, adopted in this thesis, include the course objectives established in the Aircraft Combat Survivability course taught at the Naval Postgraduate School (NPS), in additional to objectives obtained from the results of a survivability survey conducted at NPS as a part of this thesis. The educational materials, developed herein, reinforce the fundamental concepts of aircraft combat survivability through demonstration, implementation, application, and analysis of realistic design problems. Once firmly ingrained, the essential elements are then incorporated in a detailed survivability program. The program utilizes a generic aircraft and generic mission which allow students the chance to study any aircraft of interest. In addition, working the program will give students the opportunity to apply many of the concepts of survivability to a complete survivability program, from conceptual design to production. The intent of this work is to provide students, of the aircraft survivability discipline, additional educational materials designed to enhance their knowledge and proficiency of aircraft survivability in design.

DRAG STUDY AND PERFORMANCE TRADEOFFS OF A PITCHLOCKED PROPELLER ON THE P3 ORION AIRCRAFT

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A result of many malfunctions of the propeller system on the Lockheed P3 Orion is called pitchlock, a feature of the propeller pitch control mechanism that prevents low blade angles and high drag loads. Pitchlock can have serious negative impacts on the range of the aircraft, which is a critical consideration on a long-range patrol mission. The U.S. Navy P3 Fleet Replacement Squadron Fleet NATOPS Department requested an investigation of the pitchlock situation and the subsequent impact on the aircraft range. Two vortex/blade element propeller analysis computer codes were used to investigate pitchlocked, windmilling propellers. The blade angle of a decoupled propeller was predicted accurately, yet negative thrust predictions varied widely. A lack of engine data prevented use of the computer codes to investigate the coupled situation. Available negative thrust and windmilling rpm data verified by the codes was demonstrated to be useful in determining the pitchlock blade angle, the drag of the pitchlocked propeller in a windmilling condition with the engine shutdown, and the airspeed which must be decelerated to in order to prevent decoupling when the engine is shut down. Maximum range performance could not be addressed due to the lack of engine performance data.

WIND TUNNEL TEST OF THE TIER III MINUS UAV FOR TUMBLING INVESTIGATIONS

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Static and dynamic low-speed wind tunnel tests were conducted to determine the aerodynamic characteristics of a 1/25-scale Tier III Minus model. These experiments were the initial study for on-going research to investigate the tumbling susceptibility of the Tier III Minus planform. Static force and moment data were obtained for 0° to 360° angle of attack with the use of an internal strain-gage balance. Dynamic forced-oscillation tests were performed to obtain pitch damping data. Static results were as predicted and compared favorably with generic planform data collected by other investigators. However, dynamic testing failed to produce reliable pitch-damping information. Based on the geometric design of the Tier III Minus and the static pitching moment data, it is likely that the platform will experience tumbling given the proper initial conditions. However, computer simulation is required for further analysis.

A STUDY OF THE EFFECTS OF GEOMETRIC VARIATIONS ON THE FLOW CHARACTERISTICS IN THE FASTHAWK COMBUSTION CHAMBER

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A water tunnel study was conducted in support of the FASTHAWK combustor design. Five combustion chamber configurations (including a combustion can, aerogrid, turbulator and swirl devices at the dump plane) were evaluated with Laser Doppler Velocimetry (LDV) to measure profiles of turbulence intensity and axial velocity. Laser sheet flow visualization was used to analyze flow patterns of seven different combustion can designs and nozzle exit swirl.

The baseline, swirl, and aerogrid configurations produced similar flow characteristics, moderate turbulence intensity, and a large primary recirculation zone. The latter was unsuitable for short ($L/D < 1.0$) combustors. The combustion can and turbulator configurations were similar to one another with respect to axial velocity profiles and both produced a primary recirculation zone with L/D significantly less than 1.0. The turbulator configuration also produced significantly higher turbulence intensities throughout the combustion chamber, greater than any of the other configurations. The evaluation of the combustion can designs revealed the greatest impact on flow patterns results from the axial location of hole rows and that fuel injection is optimum when done near the downstream end of the primary recirculation zone.

A ROBUST METHODOLOGY TO EVALUATE AIRCRAFT SURVIVABILITY ENHANCEMENT DUE TO COMBINED SIGNATURE REDUCTION AND ONBOARD ELECTRONIC ATTACK

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This thesis examines the effect of combining radar signature reduction and onboard electronic attack (EA) capability on the survivability enhancement of a generic joint strike fighter (JSF). The missions of a generic JSF are examined, and a tactical scenario for an air-to-air mission and a strike mission are presented. The principles of signature reduction and EA using

onboard Electronic Countermeasures (ECM) are reviewed. The effect of signature level and of jammer effective radiated power (JERP) on the ability of a radar to detect the JSF are determined individually. Finally, an approach for combining the two survivability enhancement features is described, in the context of the two tactical JSF scenarios, and an EXCEL spreadsheet program entitled RCS-JERP is developed using unclassified radar and EA equipment data. Although all of the material in this thesis and in RCS-JERP are unclassified, the principles, methodology, and spreadsheet can be applied to specific (and classified) scenarios by utilizing the specific radar data, applicable mission threat analyses, and the effectiveness of the specific EA techniques employed.

PRESSURE-SENSITIVE PAINT MEASUREMENTS ON A ROTOR DISK SURFACE AT HIGH SPEEDS
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Measurement of the static-pressure distribution over the surface of a rotor disk was attempted using pressure-sensitive paint (PSP). A uniform-stress, high-speed rotor disk, fitted with a shock generator, was built, installed, and operated at speeds in excess of 20,000 RPM by a Hamilton-Standard turbine-driven fuel pump. A once-per-revolution trigger signal was converted to a transistor-to-transistor logic (TTL) format and used to gate an intensified charged-coupled device (CCD) video camera. Multiple low-intensity-level camera exposures were integrated and captured to produce a single usable image. Ten captured images were averaged to increase the image's signal-to-noise ratio and the result was used to produce an image ratio with respect to a static reference condition. Finally, a pseudo-coloring process was used to develop a color image that related intensities to both temperature and pressure distributions in accordance with the Stern-Volmer relation. Paint stripping and temperature dependence prevented the measurement of pressure at transonic speeds. The test-bed facility and acquisition techniques developed here could now be used to overcome those limitations.

AIRCREW CENTERED SYSTEM DESIGN ANALYSIS CONSIDERATIONS FOR THE MH-53E HELICOPTER
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An analysis was made of the aircrew centered system design aspects for the MH-53E helicopter. These aircrew centered design features included changes in the cockpit, aircraft weight and drag coefficient. The cockpit evaluation compared the current MH-53E cockpit configuration with design changes currently under review by the Navy. This evaluation suggests that the proposed cockpit design display change may reduce aircrew load stress and improve mission effectiveness. Changes in subsystem components may either increase or decrease the weight of the MH-53E. Similarly, changes in crew tasking may result in a need for more or less fuselage volume size. Therefore, the sensitivity of MH-53E performance to generic changes in weight and drag was investigated in order to make source assessment of equipment and crew tasking changes upon MH-53E mission effectiveness.

A SYSTEM ANALYSIS OF A NEW ASCM SIMULATOR

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This research applied a Systems engineering approach to identity the technical characteristics for an improved ALQ-17O(V) Anti-Ship Cruise Missile (ASCM) simulator. This simulator pod attaches to a F/A-18C Hornet to provide ASCM defense training. The new simulator provides a fully coherent, multi-polarization, broad band simulator that emulates all current and postulated ASCM threats through the year 2020.

A set of requirements were developed from the Operational Requirements Document (ORD) for the ALQ-170 Performance Enhancement Program (PEP) and fleet messages. Five design alternatives were examined through a number of trade-off studies in order to identify a preferred configuration. Multiple Attribute Utility Theory (MAUT) was used to score the five alternatives to determine the best possible replacement for the ALQ-170. The preferred configuration provides true "dial-a-threat" capability whereby any one of over 125 known ASCM threats are simulated upon operator command.

TESTING AND ANALYSIS OF A TRANSONIC AXIAL COMPRESSOR

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A test program to evaluate a new transonic axial compressor stage was conducted. The stage was designed (by Nelson Sanger of NASA Lewis) relying heavily on CFD techniques while minimizing conventional empirical design methods. The stage was installed in the NPS Transonic Compressor Test Rig and instrumented with fixed temperature and pressure probes. A new PC-based data acquisition system was commissioned and programmed for stage performance measurements. These were obtained at 50, 60, 65, 70, and 80% of the design speed before failure of the spinner retaining bolt led to the loss of the stage. The flow through the rotor was analyzed and the rotor performance predicted using a 3-dimensional viscous code (RVC3D). The predicted rotor performance agreed qualitatively and was numerically consistent with the measured stage performance.

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF SECOND-GENERATION, CONTROLLED-DIFFUSION, COMPRESSOR BLADES IN CASCADE

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This thesis contains a detailed experimental and numerical investigation of second-generation, controlled-diffusion compressor-stator blades at an off-design inlet-flow angle of 39.5° Investigation of the blades took place in a low-speed cascade wind tunnel using various experimental procedures. The objective of the wind tunnel study was to characterize the flow field in and around the blades at the off-design angle, and to investigate flow separation near the mid-chord for a high Reynolds number of 640,000. It was known from previous studies that boundary layer thickness on the end walls were of different thicknesses. Thus, prior to taking data, an adjustment to the end wall boundary layer thickness was attempted by insertion of an aluminum trip strip far upstream of the blades. Rake probe surveys were performed upstream and downstream of the blades in order to obtain spanwise upstream and downstream total pressure profiles. Surface flow visualization was performed on the blades using a titanium dioxide and kerosene mixture. Blade surface pressure measurements

were obtained using a 40-hole instrumented blade from which coefficients of pressure were calculated. A standard optics, two-component laser-Doppler velocimeter was used to characterize the flow field upstream, in the boundary layer on the suction side of the blades, and in the wake region. A numerical investigation was conducted using the rotor viscous code 3-D developed by Dr. Roderick Chima of NASA Lewis Research Center.

Overall, good agreement between flow visualization, blade pressure measurements, laser measurements, and numerical modeling was obtained.

CONVENTIONAL AND PROBABILISTIC FATIGUE LIFE PREDICTION METHODOLOGIES RELEVANT TO THE P-3C AIRCRAFT

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This thesis investigates conventional and probabilistic methodologies for predicting the fatigue life of critical components in the P-3C aircraft. A probabilistic damage convolution model was developed with the intent of providing quantitative predictions of life-variability. Traditional methodologies, which are based nominally on median values, lack the capacity to adequately assess variability. Aluminum 7075-T6 was tested using a fatigue Material Test System. A fatigue database was compiled from tests conducted at the Naval Postgraduate School and from literature sources.

NUMERICAL INVESTIGATION OF TUMBLING CHARACTERISTICS OF THE TIER III MINUS UAV

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In light of today's high cost military aircraft and the desire for zero fatalities in military conflict, the Unmanned Aerial Vehicle (UAV) has become increasingly more important, and with the recent use of UAVs in Operation Desert Storm, improvements in the current technologies are both indicated and desirable. However, with today's increase in threat sophistication, there has also been a recent surge of interest in the design of low observable, or stealth, aircraft. An example of a current stealth UAV is the Tier III Minus DarkStar. The DarkStar is a joint venture between the Defense Advanced Research Project Agency (DARPA), Defense Airborne Reconnaissance Office (DARO), and the Lockheed Martin (Skunk Works)/ Boeing Aircraft manufacturing teams. The DarkStar is also a tailless flying-wing aircraft and being of a flying-wing planform makes the design potentially susceptible to tumbling, a sustained autorotative pitching motion. Using the full-scale aircraft geometry, a three degree-of-freedom motion simulation program was run using coefficient data obtained from a 1/ 25-scale wind-tunnel model. Initial indications show that the Tier III Minus is capable of tumbling under initial conditions of high angle of attack and/or high pitch rate with average nose-down pitch rates of around -460 deg/sec.

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

DEVELOPMENT OF A DYNAMIC MODEL FOR A UAV

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Moments of inertia were experimentally determined and the longitudinal and lateral/directional static and dynamic stability and control derivatives were estimated for a fixed wing Unmanned Air Vehicle (UAV). High fidelity, non-linear equations of motion were derived and tailored for use on the specific aircraft. Computer modeling of these resulting equations was employed both in Matlab/Simulink and in Matrix$_x$/Systembuild. The resulting computer model was linearized at a specific flight condition, and the dynamics of the aircraft were predicted. Several flight tests were conducted at a nearby airfield and the behavior of the aircraft was compared to that of the computer model. The longitudinal dynamics as depicted by the short period mode were found to be almost identical with those predicted by the non-linear computer model. The phugoid mode was also observed and found to be in close agreement. In the lateral/directional dynamics, flight test was employed to improve the model and the parameters were modified to obtain a better match. Ultimately a reasonably accurate non-linear model was achieved as required for purposes of control and navigation system design.

EVALUATION OF THE CMARC PANEL CODE SOFTWARE SUITE FOR THE DEVELOPMENT OF A UAV AERODYNAMIC MODEL

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The CMARC panel code is evaluated to verify its accuracy and suitability for the development of an aerodynamic model of the Naval Postgraduate School (NPS) FROG Unmanned Air Vehicle (UAV). CMARC is a DOS personal computer based version of the NASA Panel Method Ames Research Center (PMARC) panel code. The core processing algorithms in CMARC are equivalent to PMARC. CMARC enhancements include improved memory management and command line functionality. Both panel codes solve for inviscid, incompressible flow over complex three-dimensional bodies using potential flow theory. Emphasis is first placed on verifying CMARC against the PMARC and NPS Unsteady Potential Flow (UPOT) panel codes. CMARC boundary layer calculations are then compared to experimental data for an inclined prolate spheroid. Finally, a complex three-dimensional panel model is developed for aerodynamic modeling of the FROG UAV. CMARC off-body flow field calculations are used to generate static-source and angle-of-attack vane position corrections. Position corrections are provided in look-up table and curve fit formats. Basic longitudinal and lateral-directional stability derivatives are also developed with CMARC data. CMARC derived stability derivatives are sufficiently accurate for incorporation into an initial aerodynamic model. Adjustments through analysis of flight test data may be required. Future CMARC studies should concentrate on the development of the damping and control power derivatives.

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

A STUDY ON THE INFRARED SUSCEPTIBILITY OF THE SH-60B SEAHAWK TO THE SA-16 GIMLET IR SAM (U)

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The survivability of a helicopter in a hostile man-made environment is a function of the aircraft's vulnerability and susceptibility. Because vulnerability is determined in the aircraft's design, susceptibility is the primary concern of the aircrew and mission planners.

The Navy's SH-60B Seahawk was initially designed for the primary mission of Undersea Warfare (USW) in the benign open ocean environment. It has since evolved into a multi-mission platform with the added roles of Antisurface Warfare (ASUW) and ASUW attack. Furthermore, the helicopter must now confront the potential threats associated with the littorals, those coastal regions characterized by high sea and air traffic.

This thesis will investigate the susceptibility of the SH-60B Seahawk to the Russian SA-16 infrared missile, a man-portable air-defense system (MANPAD). The digital computer program MOSAIC (Modeling System for Advanced Investigation of Countermeasures) will be used to evaluate the SH-60B's current infrared countermeasure systems.

INCORPORATION OF JOINT STANDOFF WEAPON STEERING COMMANDS WITH CARRIAGE AIRCRAFT

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A combined student/faculty team at the Naval Postgraduate School has been working on the conceptual design of the Unitary Joint Standoff Weapon (JSOW) Captive Air Training Missile (CATM). Previous work included modeling the JSOW's guidance and control system using the MATLAB/Simulink software package. This thesis, covering the next step in the design process, involves developing algorithms to display timely and realistic course changes to the pilot of the carriage aircraft. The carriage aircraft and algorithms were modeled using MATLAB/Simulink and XMATH/Systembuild software packages. A six-degree of freedom input device allows pilots to "fly" the carriage aircraft in a computer simulation of the JSOW CATM-aircraft interface. Steering commands are displayed on a virtual cockpit, designed by another team member using Designer's Workbench software.

STRUCTURAL DESIGN ANALYSIS OF THE TAIL LANDING GEAR BAY AND THE VERTICAL/HORIZONTAL STABILIZERS OF THE RAH-66 COMANCHE HELICOPTER

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The RAH-66 Comanche's stealth design requires the use of radar-absorbing material (RAM) on the outer skin of the aircraft. The reduced stiffness properties of RAM produce insufficient tail torsional stiffness, necessitating the use of non-radar-absorbing graphite on the outer skin of the prototype's tail section. This thesis investigates structural design modifications to increase the tail section's stiffness to allow the use of RAM on the outer skin and still meet all structural requirements. An original model represents the prototype aircraft at first flight. The goal is to create a model using RAM on the

outer skin that matches the structural stiffness of the original model. This thesis builds on earlier work conducted at the Naval Postgraduate School (NPS). Two new design modifications to the tailcone are developed. The best modification increases the torsional stiffness of a baseline model by six percent. Integrating earlier NPS modifications increases torsional stiffness by 12 percent. When RAM is applied to the outer skin of the modified model, torsional stiffness is reduced by only six percent from the baseline as compared to a 24 percent reduction with no modifications. Additional modifications to the vertical and horizontal stabilizers further increase structural stiffness and reduce weight.

ANALYSIS OF POTENTIAL STRUCTURAL DESIGN MODIFICATIONS FOR THE TAIL SECTION OF THE RAH-46 COMANCHE HELICOPTER
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The Army RAH-66 Comanche Helicopter made its first flight in January of 1996. Its current structural configuration, however, does not meet the Army's requirements for radar signature. Structural configurations of the tailcone that meet radar cross-section requirements tend to lack sufficient structural stiffness due to the presence of Kevlar in place of graphite on the outer mold line. This thesis investigates potential structural design modifications to the Comanche tailcone that would move the design closer to meeting both its structural and radar signature requirements. Structural geometry modifications with baseline (current configuration) materials increased torsional stiffness by six percent. Geometry modifications using radar signature-compliant materials reduced torsional stiffness by 15 percent. The geometry changes analyzed produce structural performance improvements insufficient to allow the use of radar-compliant materials without further geometry changes.

MODELING IN THE DESIGN AND ANALYSIS OF A HIT-TO-KILL ROCKET GUIDANCE KIT
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This thesis presents several computer models used in the design and analysis of a Hit-to-Kill Rocket Guidance Kit (HRGK). The HRGK—proposed as an inexpensive add-on kit—has the potential of converting unguided 2.75" diameter rockets into precision weapons against non-tank targets. A Naval Postgraduate School design team recently participated in a nationwide graduate student competition for the design of such a kit. The design and analysis process led the author to develop and use various computer models and simulations. This thesis documents three distinct types of computer models found useful in the design.

The first, operational effectiveness modeling, established the cost effectiveness of the NPS HRGK. The second was related to the preliminary sizing of various design aspects—ensuring the proper flow-down of system requirements into design specifications. The third was a six-degree of freedom (6DOF) simulation, developed to perform detailed analyses of the HRGK's performance.

Although the models presented in this thesis pertain to the HRGK, the basic principles apply to the design or evaluation of other missile systems, and this thesis provides general insights regarding the benefits and limitations of computer modeling in missile design.